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KOMATIITES: GEOCHEMISTRY AND GENESIS

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ABSTRACT

Some important petrographic and chemical features of peridotitic komatiites (PK) and basaltic komatiites (BK) are reviewed. New chemical data (major elements and Zr, Nb, Rb, Sr, Y, Ba, Sc, V, Ni, Cr) are presented for samples from Barberton (South Africa), Belingwe (Rhodesia), Munro (Ontario) and Yilgarn and Pilbara (Australia). The PK are divided into two types. Those of type 1, with very high CaO/Al_2O_3 (about 1.5) and low Al_2O_3/TiO_2 ratios (about 11), are depleted in Al, heavy rare earth elements (HREE), V and Sc. We refer to these as aluminum-depleted peridotitic komatiites (ADPK) and their basaltic counterparts as ADBK. The type-komatiites from Barberton fall into this category. Type 2, which contains the bulk of komatiites, has CaO/Al_2O_3 ratios of about one (*i.e.*, greater than chondritic), Al_2O_3/TiO_2 ratios of about 20 (*i.e.*, close to chondritic) and flat HREE patterns. We refer to these rocks as aluminium-undepleted (*i.e.*, AUPK, AUBK). A sequential melting model involving Al retention by orthopyroxene might explain type 2, but garnet involvement seems necessary to explain type 1. Trace-element (particularly REE) data suggest that many high-Mg basalts (11–16% MgO) are primary melts and not fractionation products from PK. In particular, one group of basalts with characteristic quench textures (STB) have light REE enrichment, flat HREE and low abundances of Ti, Zr and Y. These features probably reflect the nature of the basalt source, rather than subsequent differentiation. Discriminant diagrams such as $FeO^*/(FeO^*+MgO)$ *versus* Al_2O_3 are of little use in differentiating tholeiitic from komatiitic basalts and serve only to separate fractionated basalts from more primitive basalts. Komatiites represent large-percentage partial melts of the mantle and require very high temperatures in the original source. This implies that they are initiated deep (about $\geqq$ 400 km) in the mantle and rise owing to thermal instability. Post-Archean komatiites, although rare, are known to occur in the Proterozoic Cape Smith–Wakeham Bay province of northern Québec. We do not include low-Ti, high-Mg ophiolitic basalts in the komatiite group.

SOMMAIRE

On passe en revue quelques caractéristiques pétrographiques et chimiques importantes de komatiites péridotitiques (PK) et basaltiques (BK), et l'on présente des données chimiques nouvelles (éléments majeurs, Zr, Nb, Rb, Sr, Y, Ba, Sc, V, Ni, Cr) pour des échantillons de Barberton (Afrique du Sud), Belingwe (Rhodésie), Munro (Ontario), Yilgarn et Pilbara (Australie). On distingue deux types de PK: le premier, à rapport CaO/Al_2O_3 très élevé ($\sim$ 1.5) et faible rapport Al_2O_3/TiO_2 ($\sim$ 11), comporte les PK appauvries en Al, terres rares lourdes (HREE), V et Sc, que nous appelons PK appauvries en aluminium (ADPK), et les BK analogues, dites ADBK. Les komatiites-types de Barberton en donnent un exemple. La plupart des komatiites sont du type 2; les rapports CaO/Al_2O_3 et Al_2O_3/TiO_2 s'élèvent, respectivement, à 1 (*i.e.*, surpassant la valeur chondritique) et $\sim$20 (proche des valeurs chondritiques); pour ces roches la courbe d'enrichissement relatif en HREE est en palier. Nous les appelons roches non-appauvries en aluminium (AUPK, AUBK). Un schéma de fusions successives, avec rétention d'Al par l'orthopyroxène, pourrait expliquer le type 2; quant au type 1, il semble qu'on ne puisse l'expliquer que par l'intervention du grenat. Les éléments en traces, surtout les terres rares, indiquent que de nombreux basaltes magnésiens (11-16% MgO) proviennent de bains de fusion primaires et ne sont pas des produits de cristallisation fractionnée de PK. En particulier, un groupe de basaltes à textures de trempe caractéristiques (STB) possèdent un enrichissement en terres rares légères, une courbe en palier pour l'enrichissement en terres rares lourdes et de faibles teneurs en Ti, Zr et Y, caractères qui reflètent probablement la nature de la roche-mère plutôt que les effets d'une différenciation postérieure. Les courbes de $FeO^*/(FeO^* + MgO)$ en fonction d'Al_2O_3 sont impuissantes à faire la distinction entre basaltes tholéitiques et komatiitiques; elles ne peuvent servir qu'à séparer les basaltes différenciés des basaltes originels. Les komatiites représentent des produits de fusion partielle dans le manteau, ce qui requiert des températures très élevées à la source et, par conséquent, implique qu'elles se sont formées en profondeur ($\geqslant$ 400 km) et que leur montée est due à l'instabilité thermique. Les komatiites post-archéenes sont rares; on les trouve dans la ceinture protérozoïque allant du cap Smith à la baie Wakeham, dans le nord du Québec. Les basaltes riches en Mg et pauvres en Ti qui font

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partie du cortège ophiolitique sont exclus du groupe des komatiites.

(Traduit par la Rédaction)

INTRODUCTION

In the course of their extensive descriptions of the Barberton area, Viljoen & Viljoen (1969a, b) noted the abundance of unusual ultramafic rocks in the lower parts of the Onverwacht Group. They termed these ultramafic rocks *peridotitic komatiites* (PK) and called what they believed to be genetically related basic rocks *basaltic komatiites* (BK). Peridotitic komatiites have now been documented in the Archean of Canada (*e.g.*, Arndt *et al.* 1977), Finland (Blais *et al.* 1979), Rhodesia (Nisbet *et al.* 1977), Western Australia (*e.g.*, Nesbitt & Sun 1976) and India (Nesbitt, unpubl. data).

The name *komatiite* now seems to have general acceptance although paradoxically there is no consensus as to the precise definition. Similarly, although the term *basaltic komatiite* is used consistently in the literature, the distinction between various basaltic types as well as the broad subdivisions between basaltic and peridotitic komatiites is nowhere acceptably defined. Despite this nomenclatural incongruity, komatiites represent an important group of igneous rocks that have important implications in such diverse fields as mantle chemistry and mineral exploration.

In this contribution, we are principally concerned with the geochemical characteristics of the group, and data from South African, Rhodesian, Canadian and Australian komatiites are presented. The South African material is from the type area of Barberton; some of the data represents reanalysis by us of powders originally used in the study of Viljoen & Viljoen (1969a, b). The remaining samples were collected by one of us (R.W.N.). Rhodesian material is principally that used by Nisbet *et al.* (1977) and reanalyzed by us. The Canadian samples are from the Munro locality, originally described by Pyke *et al.* (1973); they were collected by one of us (R.W.N.). The Australian material comes from several localities in the eastern part of the Yilgarn Block and from the western Pilbara Block. Further details of sample locations are given in Nesbitt & Sun (1976), Sun & Nesbitt (1978a) and Table 1 (this paper).

KOMATIITE: DEFINITION AND NOMENCLATURE

Peridotitic komatiite

In their original description of komatiites, Viljoen & Viljoen (1969a, b) stressed the field, petrographic and geochemical characteristics of the proposed new class of igneous rocks. Unfortunately, they did not formally define the class, but instead emphasized those characteristics that set the rocks apart from other high-Mg rocks. A decade later, about the only aspects of the original description that have not been modified by later workers are the field and textural characteristics of peridotitic komatiites. The textures were termed *crystalline quench structures* by Viljoen & Viljoen (1969b) but now are more commonly known as *spinifex textures* (Nesbitt 1971). The megascopic, skeletal, bladed olivine texture is diagnostic of crystal growth in an ultramagnesian ($\geqslant 20\%$ MgO) liquid and is, in our opinion, the prime characteristic of the peridotitic komatiite (PK) group. Without this characteristic, the major-element chemical features of the PK could in many cases be said to be the result of crystal accumulation and could be matched by any ultramafic rock with significant clinopyroxene or calcic amphibole (Brooks & Hart 1974).

In their discussion of geochemical work on PK, Viljoen & Viljoen (1969b) concentrated on the differences between PK and other well-known high-Mg rocks. In particular, they emphasized the consistently low alumina content and exceptionally high Ca/Al ratio [an average value of 1.59 for the Ca/Al ratio of komatiites was quoted by Viljoen & Viljoen (1969b, p. 110); it is evident from their Figure 6a that they meant the average to refer to CaO/Al_2O_3], which they regarded as "the most striking attribute of the Komati formation peridotites." This feature also formed the connecting link between peridotitic and basaltic komatiites that occur within the same stratigraphic section. Other features noted in the original description were the low alkali contents of the PK which effectively separated them from basaltic kimberlites, ankaramites and limburgites; the alkalis are marginally lower than in other peridotites. Viljoen & Viljoen (1969b) also pointed out that PK are more ultramafic than picrites and could be distinguished from peridotites by their higher Fe/Mg ratio. Of these three chemical features (high Ca/Al, low alkalis and Fe/Mg ratio), the high Ca/Al feature has been emphasized by later workers. This is understandable in the light of the effect of alteration on alkali content, which makes this parameter of minor importance. Furthermore, the Fe/Mg ratio is difficult to apply because the cumulate members of the komatiite class have low Fe/Mg ratios approaching that of other peridotites.

TABLE 1 CHEMICAL ANALYSES OF MATERIAL USED

	1	2	3	4	5	6	7	8	9	10	11
Locality:	Barberton (South Africa)										
Sample No.:	VU32B	331/79	331/80	331/81	331/776	331/777A	331/783	SG3	331/784	331/779	331/780
Rock type:	PK	STPK	STPK	STPK	PK	STPK	STPK	BK	BK	BK	BK
SiO_2	44.25	47.22	48.56	47.95	47.23	48.41	46.71	49.10	49.60	53.65	52.92
Al_2O_3	2.85	4.10	4.78	4.64	3.79	4.40	4.45	6.67	5.21	4.42	8.14
Fe_2O_3	10.60	13.39	12.10	12.86	12.32	12.02	13.71	13.34	14.61	11.10	11.87
MnO	.17	.21	.23	.24	.19	.19	.20	.29	.18	.18	.19
MgO	37.61	27.37	24.78	25.29	28.67	26.26	26.69	21.20	19.58	14.94	11.81
CaO	4.36	6.44	7.88	7.40	6.45	7.32	7.35	9.24	9.59	12.70	11.53
Na_2O	.16	.69	.85	.84	.15	.71	.28	.35	.38	1.89	2.29
K_2O	.01	.07	.11	.09	.01	.04	.01	.04	.02	.05	.04
TiO_2	.23	.38	.45	.42	.37	.41	.42	.36	.50	.50	.67
P_2O_5	.02	.03	.04	.04	.04	.03	.04	.06	.05	.04	.07
LOI	7.21	5.90	5.00	5.10	6.33	5.37	5.54	3.91	3.43	1.08	.92
Zr	12	25	28	27	29	25	26	17	31	25	44
Nb	1.5	2	2	3	2	2	2.5	2	3	3	2.5
Rb	1	1	2	2	1	1	2	3	1	2	1
Sr	11	44	48	46	16	36	30	24	17	28	33
Y	4	9	10	10	9	9	9	8	11	10	17
Ba	10	12	13	25	5	14	6	58	6	31	28
Sc	14	20	25	23	22	25	25	22	27	42	43
Ni	1950	1420	1115	1380	1417	1233	1229	1150	1066	421	138
Cr	1890	2680	3130	2960	2329	2875	2942	4860	2591	2304	904
V	75	113	140	129	117	134	137	162	162	174	238

	12	13	14	15	16	17	18	19	20	21	22
Locality:	Barberton (continued)				Belingwe (Rhodesia)					Yakabindie	Mt. Burges
Sample No.:	34J	40J	LV4	V11	331/514	331/515	331/483	331/487	331/488	331/348	331/94
Rock type:	B	B	B	B	BK	PK	PK	STPK	STPK	PK	PK
SiO_2	52.34	51.39	51.18	53.53	47.93	44.34	46.09	46.61	46.66	44.06	44.40
Al_2O_3	15.04	15.15	14.64	13.38	9.37	4.27	6.05	6.25	6.00	4.55	8.03
Fe_2O_3	10.74	11.58	11.15	13.06	12.65	11.06	11.62	11.94	12.04	10.55	12.02
MnO	.22	.19	.20	.21	.34	.20	.23	.23	.24	.20	.14
MgO	6.51	8.36	9.08	6.35	16.76	35.11	28.72	28.06	29.45	35.30	26.70
CaO	10.59	11.82	9.63	8.70	11.83	4.32	6.17	5.79	5.22	4.82	7.17
Na_2O	3.86	1.39	2.13	3.61	.77	.15	.71	.22	.22	.28	.98
K_2O	.11	.08	2.17	.47	.05	.08	.20	.45	.25	.02	.12
TiO_2	.71	.71	.62	1.07	.46	.21	.27	.29	.28	.23	.35
P_2O_5	.07	.07	.06	.13	.05	.02	.02	.02	.02	.01	.03
LOI	2.62	2.63	2.09	1.27	2.72	7.98	3.96	7.28	8.01	6.69	2.20
Zr	40	40	30		21	9	12	12	11	13	17
Nb	2.5	2	2		2.5	1	2	1	1	.5	2
Rb	3	1	50		2	4	3	14	9	4	3
Sr	159	160	122		44	13	29	23	27	22	21
Y	19	19	15		9	4	6	6	6	4	8
Ba	27	18	111		40	8	10	60	40	7	20
Sc	38	42	40		37	15	23	23	21		29
Ni	165	165	160		450	1960	1665	1390	1555	1820	1160
Cr	250	270	330		1310	3530	2850	2610	2600	3000	2900
V	250	265	255		190	80	108	118	107	94	143

TABLE 1. CHEMICAL ANALYSES OF MATERIAL USED

	23	24	25	26	27	28	29	30	31
Locality:	Scotia	Pilbara (W. Australia)			Marshall Pool (W. Australia)				Munro (Canada)
Sample No.:	SD4/341	331/496	331/497	331/498	331/529	331/531	331/532	331/533	422/93
Rock type:	PK	STPK	STPK	STPK	PK?	STPK	STB	STPK	PK
SiO_2	43.51	46.68	47.63	43.61	47.96	48.66	47.06	47.71	44.07
Al_2O_3	4.45	4.10	3.96	3.36	9.16	9.21	9.23	8.44	5.47
Fe_2O_3	10.06	12.75	12.07	14.39	13.84	12.33	13.92	12.14	10.54
MnO	.18				.24	.22	.27	.19	.19
MgO	37.79	29.55	27.90	28.43	18.05	18.95	18.79	20.90	33.92
CaO	3.49	5.78	6.70	8.01	9.89	8.83	9.83	9.63	5.20
Na_2O	.18	.46	.56	.15	.6	1.24	.74	.30	.32
K_2O	.01	.11	.12	.05	.05	.04	.08	.05	.13
TiO_2	.22	.37	.37	.40	.52	.50	.49	.45	.21
P_2O_5		.03	.02	.03	.05	.04	.05	.05	.02
LOI	8.50	7.72	6.54	14.40	4.32	4.17	4.46	4.84	5.00
Zr	11	21	21	17	29	27	25	25	12
Nb	1	1	1	1	1	2	2	1	1
Rb	1	2	2	2	2	1	2	3	2
Sr	17	28	31	167	14	24	17	6	18
Y	4	6	7	7	12	10	11	10	7
Ba	5	15	15	45	20	10	10	25	7
Sc	17	22	22	21	37	35	36	33	20
Ni	1960	1630	2025	1640	680	720	710	885	1530
Cr	2120	2675	2710	2375	2280	2720	3060	2790	2290
V	95	114	110	123	197	195	192	175	103

STPK: spinifex-textured peridotitic komatiite; KB: komatiitic basalt in the sense of Viljoen & Viljoen (1969a,b); PK: peridotitic komatiite in which the olivine is not skeletal; B: basalt, represents the tholeiites from the Hooggenoeg and Komati Formations (Viljoen & Viljoen 1969a,b). Some samples from Barberton carry the original numbers of Viljoen & Viljoen (1969a,b); the analyses represent new data obtained on the original powders. Other Barberton samples: 331/776 from AU5 locality, 331/777A, 331/779 from close to locality VU30, 331/780 close to AB9, 331/783 and 331/784 from the small south-flowing tributary immediately west of the main collection area of Viljoen & Viljoen (1969a,b). Samples 331/483, 331/487, 331/488 have been reported on by Nisbet *et al.* (1977) and represent their samples SF134, NG157, NG208, respectively. All analyses in Table 1 were carried out at the University of Adelaide; most elements were determined by X-ray fluorescence (analytical details were reported by Nesbitt & Sun 1976). REE elements were determined by isotope dilution (Sun & Nesbitt 1978a). The analyses are reported on a dry (950°C) basis and total iron as Fe_2O_3. Major elements and loss on ignition (LOI) expressed as percentages, trace elements in parts per million. Analyses in this table as well as those reported in Nesbitt & Sun (1976) and Sun & Nesbitt (1978a) were used to construct figures.

This parameter (normalized against Al_2O_3 content) has even been used in the reverse sense to that recommended by Viljoen & Viljoen (1969b), in order to differentiate komatiitic and tholeiitic rocks (Arndt *et al.* 1977).

Subsequent descriptions of komatiites have led to significant modifications of the list of features noted by Viljoen & Viljoen (1969a, b). Nesbitt (1971) described texturally identical ultramagnesian flows from Western Australia and noted that their Ca/Al ratio was significantly lower than the type peridotite komatiite. Subsequently, Brooks & Hart (1974) suggested that komatiites should have CaO/Al_2O_3 ratios greater than one and that the low TiO_2 content (a feature not mentioned in the original descriptions) be emphasized. At the present time, work on Canadian (*e.g.*, Arndt *et al.* 1977), Rhodesian (Nisbet *et al.* 1977), Finnish (Blais *et al.* 1979) and Australian (*e.g.*, Nesbitt & Sun 1976) peridotitic komatiites has demonstrated that the most common variety has a CaO/Al_2O_3 ratio of about 1, *i.e.*, slightly greater than chondritic. Purvis (1978) refers to these rock types as aluminum-undepleted peridotitic komatiites (AUPK) and the less common Barberton type as aluminum-depleted peridotitic komatiites (ADPK). We adopt this terminology here in preference to STPK–h, *etc.*, as used by Sun & Nesbitt (1978a). The geochemical basis for this nomenclature is discussed in the section on geochemistry.

In our view, parameters such as Ca/Al and TiO_2 content should not be the prime factors used in the identification of PK. Undoubtedly, the best parameter is the presence of spinifex textures among some members of the class, which indicates the development of ultramagnesian liquids. These textures were originally subdivided and called "plate, radiating and porphyritic" spinifex by Nesbitt (1971) but subsequently, the term "random" replaced radiating. "Harrisitic-spinifex" (Nesbitt 1971) is now withdrawn because the rock does not represent a liquid composition but is a crescumulate growth (*cf.*, Wager & Brown 1968). For reasons outlined elswhere (Sun & Nesbitt 1978a), we suggest that the term "string-beef" clinopyroxene spinifex texture (Arndt *et al.* 1977) also falls into the non-liquid category. In addition, there has been some confusion over the term *porphyritic spinifex* because skeletal grains can settle to form a cumulate rock. As in our view spinifex texture should refer to *in situ* crystallization of a liquid, such a cumulate rock cannot strictly be said to have "spinifex texture". Clearly, the subject of classification and nomenclature of the texture needs further evaluation.

BASALTIC KOMATIITES

Whereas spinifex texture and trace-element characteristics help to identify peridotitic komatiites, basaltic komatiites (BK) remain an enigma. Little new information has been published from the type area since the original description (Viljoen & Viljoen 1969a) but there has been a proliferation of descriptions from other localities (*e.g.*, Williams 1972, Arndt *et al.* 1977, Nesbitt & Sun 1976, Sun & Nesbitt 1978a, Naldrett & Turner 1977, Gale 1973). The result has been a considerable modification and widening of the definition.

Viljoen & Viljoen (1969a) subdivided the basalts into Barberton, Badplaas and Geluk types, based largely on MgO content (10%, 15% and 20%, respectively) and high CaO/Al_2O_3 ratio. Their other characteristics (textures, mineralogy, *etc.*) were not emphasized; without further information from the type area, they are of little practical use as criteria for identification. In the type area, the Barberton-type komatiitic basalts seem to be the predominant types; they have the lowest Ca/Al and MgO content of the three basaltic types. The Badplaas type, characterized by a very high CaO/Al_2O_3 ratio (> 2), may not represent a liquid composition. Viljoen & Viljoen (1969a) commented that these basalts are better termed metapyroxenites and that most of the material occurs as "massive, possible near contemporaneous sills." The occurrence of cumulate clinopyroxene would certainly help explain the unusual features of this basalt type. Geluk-type basalts have the highest MgO content of the basaltic types and occur high in the section, generally away from the ultramagnesian PK. The Ca/Al ratio of this variety is slightly higher than the Barberton type, but Viljoen & Viljoen (1969a) also describe a low-Al type which has a CaO/Al_2O_3 ratio of 2.5. The Geluk type requires more detailed work on the type material.

In a study of basalts from the Eastern Goldfields of Western Australia, Williams (1972) described a "high-Mg" type with a range of MgO from 8 to 24%. In his description, Williams (1972) emphasized the textural characteristics of skeletal crystallization and an abundance of glass. Sun & Nesbitt (1978a) referred to this type as spinifex-textured basalt (STB) because the general nature of the quench clinopyroxene mimics on a fine scale the texture of peridotitic komatiites. We are not aware of similar material being described from the Barberton area.

In a description of komatiites from Munro township, Arndt *et al.* (1977) have suggested a three-part classification in which BK have less than 12% MgO, pyroxenitic komatiites have less than 20% MgO and peridotitic komatiites have more than 20% MgO. In an alternative scheme, Naldrett & Turner (1977) suggested that the terms magnesian basalts, pyroxenites, pyroxene peridotites and peridotites (or peridotitic komatiites) be used for the ranges 10–12, 12–20, 20–30 and over 30% MgO (anhydrous). Such schemes, adopted to cover the needs of a specific area, have thus completely modified the original Viljoen & Viljoen (1969a) terminology.

In reviewing the occurrence, petrology and geochemistry of basaltic komatiites, two major problems become evident: (a) is a simple fractional crystallization from a PK liquid or a partial-melting model sufficient to explain the chemical features or will a variety and combination of such processes produce broadly similar liquids? (b) is it possible to distinguish between fractionated basaltic komatiites and near-primary tholeiites, particularly where the rocks are altered?

The principal evidence for the crystal differentiation mechanism is the presence of thick differentiated flows in the Munro area of Ontario; Arndt *et al.* (1977) have described a thick flow (Fred's flow) in which a series of spinifex-textured lavas with a range of compositions from about 17 to 12% MgO underlie a parental flow-top breccia with about 20% MgO. The central part of the thick flow is made up of gabbro (about 8% MgO and quartz-bearing) and the base of the flow has olivine and pyroxene cumulates. Whereas these data certainly suggest that the mechanism of crystal fractionation can operate in the production of lavas lower in MgO, there is other evidence suggesting that it may not be a dominant process. For example, the data of Arndt *et al.* (1977) show that within the lavas there is a compositional break in the 15–20% MgO range, *i.e.*, in the region in which differentiation of a 20% MgO lava is supposed to produce lower MgO rocks. However, a more serious objection is seen in the rare-earth (REE) data. Whitford & Arndt (1979) show that fractionation within Fred's flow produces a series of parallel REE patterns in which the light REE (LREE) slope in particular shows very little change, thus supporting the fractional crystallization model. However, the data of Arth *et al.* (1977) on a series of peridotitic, pyroxenitic and basatic komatiites from the Munro area show a range of LREE patterns with significantly different slopes, indicating they cannot be generated by fractional crystallization of one parental liquid. As a consequence, Arth *et al.* (1977) concluded that both fractional crystallization and partial melting are involved in the formation of basaltic komatiites.

The question of distinguishing between tholeiitic and komatiitic rocks is in part a geochemical one; Arndt *et al.* (1977) and Naldrett & Turner (1977) have suggested the use of certain discriminant diagrams to separate the basaltic types. We will return to this problem after a discussion of the broad aspects of komatiite geochemistry.

GEOCHEMISTRY OF KOMATIITES

The broad geochemical relationships of komatiites have been described by us in several previous publications (Nesbitt & Sun 1976, Sun & Nesbitt 1977, 1978a). In this contribution we intend to focus on a few geochemical problems posed by komatiites; chief among these are: the significance of the high Ca/Al ratio; the use of discriminant diagrams to distinguish komatiites from tholeiites; the nature of post-Archean magnesian liquids that may be komatiites. The discussion of these problems is carried out in the context of our own chemical data on a series of komatiites from widely separated Archean terrains (Table 1). Such data can only be used if the analyses represent the original composition of the rocks; in the following discussion we comment on this aspect of komatiite research.

Alteration

There can be no doubt that there has been chemical modification of Archean greenstones; there is a general consensus that alkali and alkaline-earth metals such as K, Na, Rb, Ba and Sr are quite mobile. It also has been claimed (*e.g.*, Pearce & Cann 1973) that elements such as Ti, Zr, Y, Sc, Nb and REE are "immobile" and hence can be used as petrogenetic indicators. However, some studies (*e.g.*, Frey 1969, Frey *et al.* 1974, Wood *et al.* 1976, Hellman & Henderson 1977, Condie *et al.* 1977) show that under many circumstances this may not be the case. Based on REE studies, Sun & Nesbitt (1978a) suggested that the light REE are more mobile than the heavy REE and that Eu and Ce are sometimes more mobile than the other REE (presumably due to the existence of different oxidation states of Eu and Ce as compared to the other REE elements).

Several techniques are currently employed to overcome the alteration problem and aid the selection of samples. Many (*e.g.*, Gélinas *et al.* 1977) use factors such as volatile and alkali content in combination with textural studies. Our approach has been to select a series of samples with original textures and some original mineralogy preserved. Using this method, Nesbitt & Sun (1976) and Sun & Nesbitt (1978a) established a set of guidelines based on the consistency of chemistry among a group of samples from the same area. For example, elemental ratios such as Ti/Zr or Zr/Nb should be consistent and should correlate with the REE patterns (Sun *et al.* 1979). This study also demonstrated that in Archean greenstones, values of Ti/Zr and Ti/Y are very commonly close to 110 and 290, respectively; the fact that these are chondritic is an indication that they represent original liquid compositions. Another useful ratio is TiO_2/P_2O_5 (close to 10 ± 1), which conforms to the estimated value of the ratio for the earth's mantle (Sun & Nesbitt 1977).

Hence the guidelines are dominated by a search for regularities in the geochemistry and the belief that there should be consistency of elemental ratios in magmatic liquids which cannot be matched by metamorphic processes. In the following section we illustrate this point in relation to the Ca/Al characteristics of the type komatiites.

CaO/Al_2O_3

Although the original definition of komatiite (Viljoen & Viljoen 1969a, b) strongly emphasized the high CaO/Al_2O_3 ratio, several authors (*e.g.*, Nesbitt 1971, Williams 1972, Nesbitt & Sun 1976, Arndt *et al.* 1977) have pointed out that this is not a universal feature of ultramafic material which on textural criteria would be classed as PK. Apart from the Barberton material we have recognized only a few other occurrences which have the high CaO/Al_2O_3 ratio. In Western Australia, these are Forrestania (Purvis 1978), Ravensthorpe (Baxter 1971) and the western part of the Pilbara Block (this paper). As a consequence it has been suggested that the high ratio should be relaxed as a criterion and that the definition should allow the ratio to be close to or greater than one (*e.g.*, Arndt *et al.* 1977). We note that even if the ratio of one is adopted this is still higher than that found in common mafic melts (*e.g.*, MORB) which have a ratio of about 0.8. Hence, despite these suggestions regarding the definition, we are still faced with the problem of understanding the high CaO/Al_2O_3 ratio of the most abundant PK and the even higher ratio of the Barberton-type komatiites. The principal question is whether the ratio is a magmatic or metamorphic one; if magmatic, why is it so high? Condie *et al.* (1977) noted that some types of metamorphism (particularly epidotization) release Al, hence increasing the Ca/Al value; *i.e.*, alteration is promoting a komatiitic characteristic. This is a disturbing conclusion because most post-Archean "basaltic komatiites" have been recognized on the basis of the high ratio. However, it is possible to evaluate the data on Barberton and other material; this suggests that in general the high ratio is not an alteration phenomenon. Figures 1a and 1b are Al_2O_3 *vs.* TiO_2 and CaO *vs.* TiO_2 plots for the Archean komatiites reported in Table 1. Whereas there is general scatter about the chondritic line for the Ca–Ti plot, the bimodal distribution in the Al–Ti plot is obvious. We believe this to be a most important fact in komatiite genesis because the Barberton material has Al_2O_3/TiO_2 ratios of about 11 whereas most other komatiites have ratios close to chondritic (about 20). The reasoning behind the selection of these particular plots is as follows: if spinifex-textured peridotitic komatiites (STPK) are the products of large amounts of melting and Ti is regarded as completely incompatible at high levels of melting (> 15%), then all of the Ti should be in the melt. The same should be true for the Ca and Al provided there is no residual phase in the source capable of retaining significant amounts of these elements. Thus in a series of MORB-type liquids representing increasing amounts of melting (*i.e.*, Ti decreases) the Al_2O_3/TiO_2 and CaO/TiO_2 ratios increase until a plateau is reached which represents the release of all the Al and Ca into

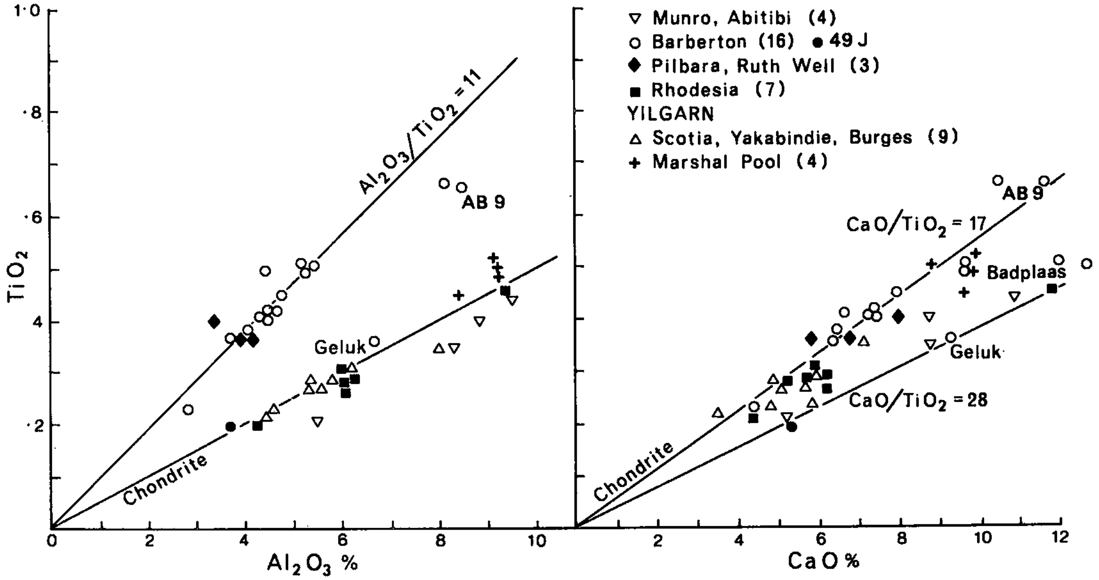

FIG. 1. (a) TiO_2–Al_2O_3 diagram illustrating the position of Barberton komatiites relative to other komatiites. With the exception of the two Barberton samples labelled AB9, all samples have greater than 15% MgO (b) TiO_2–CaO diagram for the same samples.

the melt (Fig. 2). Further melting will alter the absolute abundances (by dilution) but not the ratios. It follows that in a simple case of a single high-degree melting event, the Al/Ti and Ca/Ti ratios of STPK will be that of their source.

As Figure 1b shows, most of the Barterton material has close to chondritic Ca/Ti ratios whereas their Al/Ti ratios are well below the chondritic value. We conclude that the type Barberton material is depleted in Al and that this produces the high Ca/Al originally observed

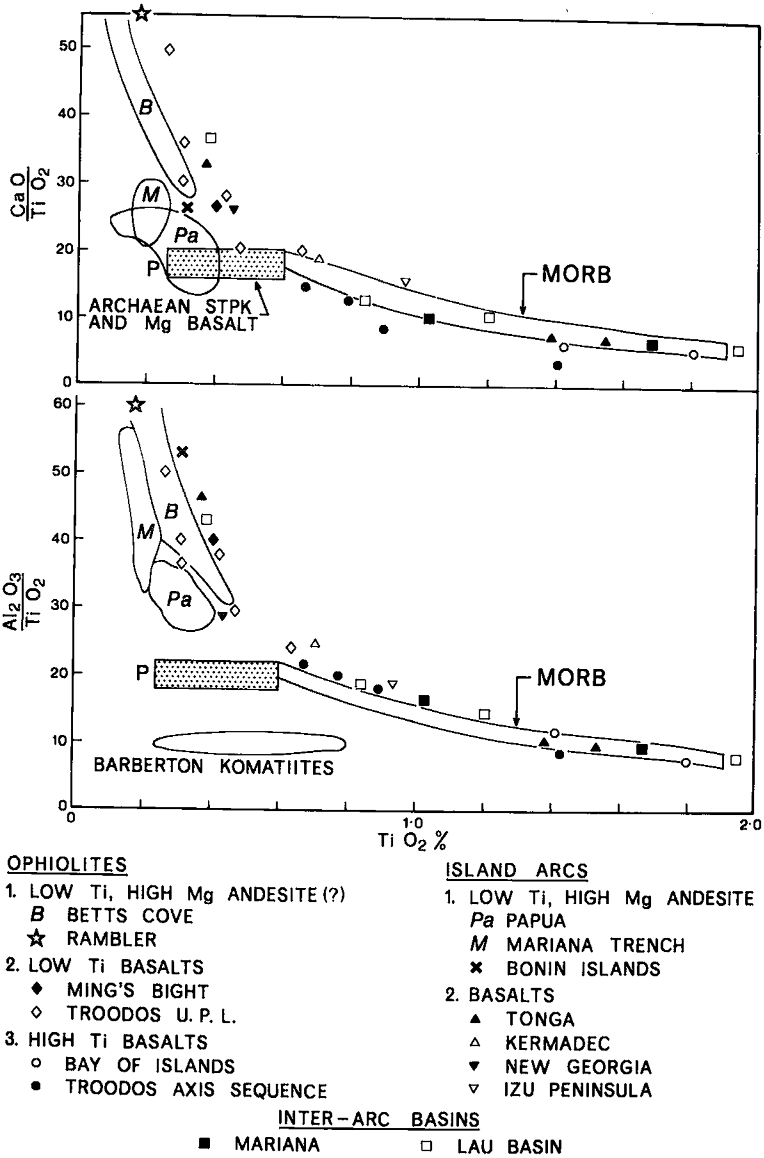

FIG. 2. (a) CaO/TiO_2 *vs.* TiO_2 diagram; (b) Al_2O_3/TiO_2 *vs.* TiO_2 diagram, both for STPK, MORB, basalts from ophiolites, island arcs and inter-arc basins. As the degree of partial melting increases, TiO_2 decreases and CaO/TiO_2, Al_2O_3/TiO_2 ratios of MORB approach Archean STPK and model pyrolite (P). The general position of Barberton komatiites (samples with spinifex texture only) is given, and illustrates that low Al_2O_3 is responsible for their high CaO/Al_2O_3 ratio. Data sources are available from the authors on request.

by Viljoen & Viljoen (1969a, b). Purvis (1978) has proposed that those komatiites with low Al_2O_3/TiO_2 ratios be called aluminum-depleted peridotitic komatiites (ADPK) and those with close to chondritic ratios, aluminum-undepleted peridotitic komatiites (AUPK).

The simple model outlined above can be modified in a number of ways. For example, crystal accumulation into or fractionation out of the liquid will affect the Al/Ti and Ca/Ti distribution if the crystal(s) contains these elements. This is particularly true for the basaltic rocks in which plagioclase and pyroxene are involved; for this reason we have not plotted the fractionated Barberton tholeiites. Similarly, we believe the high CaO/TiO_2 ratio found in the Badplaas-type (sample VB1 and 331/779) and Geluk-type (SG3) basaltic komatiite (Fig. 1b) could be due to clinopyroxene accumulation. However, if this interpretation is correct, it is puzzling that the Badplaas-type samples have values of Al_2O_3/TiO_2 characteristic of Barberton materials, whereas sample SG3 has a near-chondritic value (see also Fig. 3).

Another puzzling specimen is 49J, which has the highest MgO content of the Barberton STPK material. This sample was used by Green *et al.* (1975) to experimentally fix the 1 atm liquidus temperatures of komatiites at 1650°C. However, it differs from the majority of other Barberton STPK samples because it has a near-chondritic Al/Ti ratio (Fig. 3) and a high Ca/Ti ratio (Fig. 1b). Hence this sample, like the other Barberton STPK, has a high Ca/Al ratio, but the reasons for this are quite different. As we will discuss later, this sample has a number of characteristics (*e.g.*, flat rare-earth pattern) that distinguish it from other Barberton samples.

Another factor that may modify the Al/Ti and Ca/Ti plots is alteration. All komatiites are altered; mineralogically this manifests itself in assemblages of serpentine, chlorite, talc, tremolite and carbonate. Figures 4a and 4b, plots of $MgO–Al_2O_3$ and MgO–CaO, show a tight correlation of Mg–Ca but a dispersed pattern for Mg–Al. This distribution pattern is unlikely to be controlled by metamorphism, as in the Mg–Al plot, the various geographically dispersed komatiites fall into their own groupings, whereas no such pattern is evident in the Mg–Ca plot. The geographic groupings in Figure 4a are significant in that they demonstrate the different bulk compositions of various komatiites. The $MgO–Al_2O_3$ line on this diagram

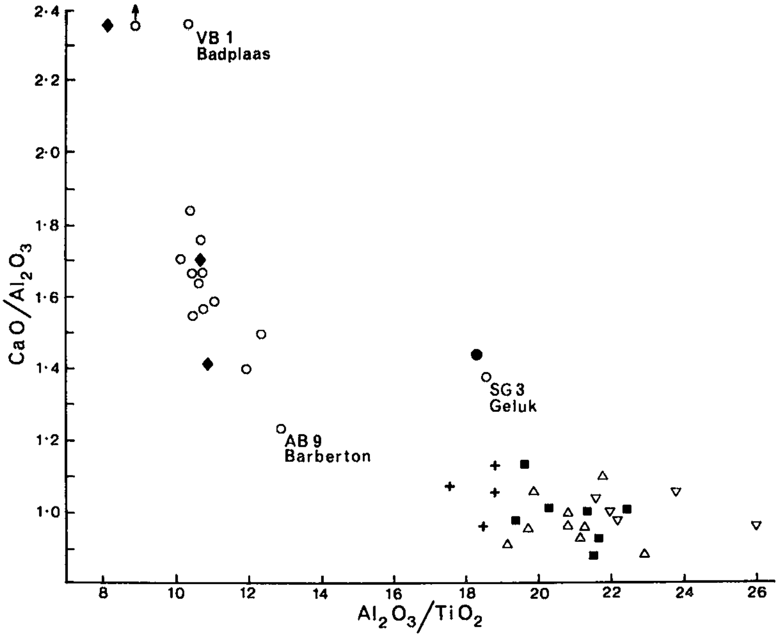

FIG. 3. CaO/Al_2O_3 *vs.* Al_2O_3/TiO_2 diagram for komatiites used in this study. The chondrite value for Al_2O_3/TiO_2 is 20.4; only two of the Barberton samples approach this value. The spread of CaO/Al_2O_3 ratio at fixed Al_2O_3/TiO_2 is emphasized by VB1 (cumulate pyroxenite?) and a Pilbara STPK (Ca metasomatism?). Symbols as in Figure 1.

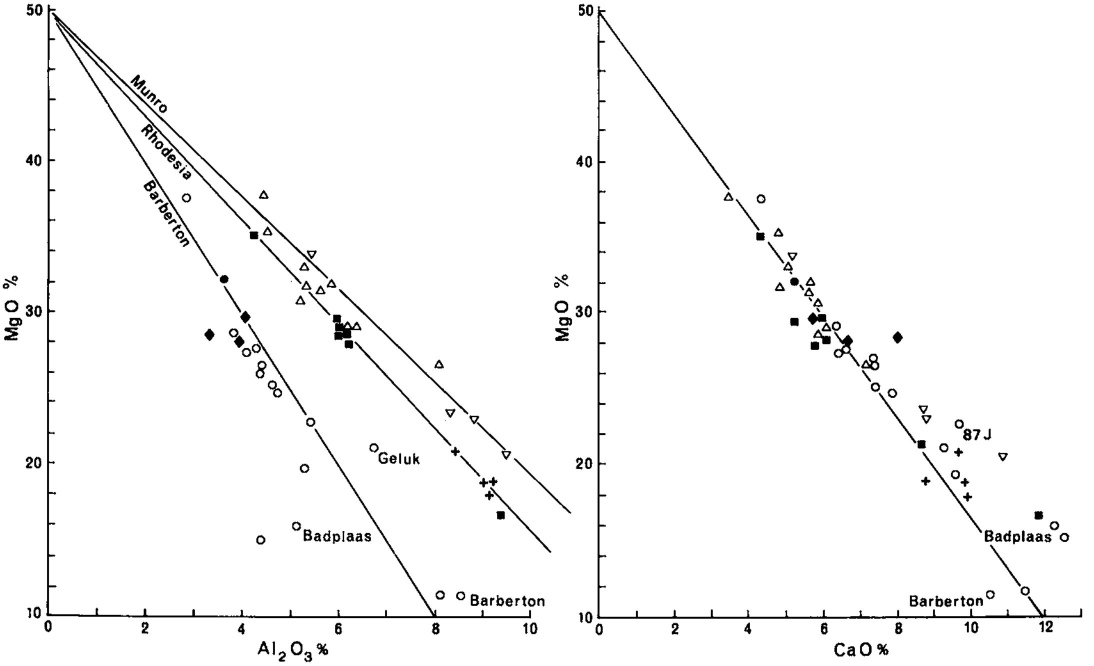

FIG. 4. (a) MgO–Al_2O_3 diagram. Lines are drawn arbitrarily through data points from different areas to draw attention to the geographic spread. (b) MgO–CaO diagram for same data points. Anomalous Barberton samples are labeled. Symbols as for Figure 1.

represents an olivine control for each of the groups and its slope is therefore controlled by the starting composition. It is apparent from this that the Barberton material has an inherently lower Al_2O_3 content than other komatiites, producing the characteristically low Al_2O_3 ratios.

Samples such as 331/498 do show the influence of alteration. This sample, from the Pilbara region of Western Australia, is strongly carbonated and has a 14% loss on ignition. On the MgO–CaO plot (Fig. 4b) it falls well away from the general trend of other samples with comparable MgO content. However, at lower MgO contents ($<$ 20% MgO), we suggest that crystal fractionation may be the most important contributor to the Mg–Ca scatter.

Sequential melting and abnormally high Ca/Al ratios

The bulk of peridotitic komatiites have depleted light-rare-earth patterns (Arth *et al.* 1977, Sun & Nesbitt 1978a) which is also a feature of normal MORB (*e.g.*, Kay *et al.* 1970). This depletion has been interpreted as a result of melting of a mantle source in which a small amount of the melt is retained in the residue and which on further melting produces a MORB-type melt with a depleted LREE pattern (*e.g.*, Langmuir *et al.* 1977). The overall slope of the REE pattern is controlled by the original source character, the degree of melting and the amount of first melt retention. This model is similar to the sequential melting model of Arndt (1977) who proposed that the process can explain the abnormally high CaO/Al_2O_3 ratios of Barberton komatiites. In this model the first liquid produced is in equilibrium with pyroxene and olivine whereas the garnet component is completely removed into the melt. Arndt (1977) claims that the residue of such a melt would be depleted in aluminum relative to calcium and hence further melting would produce a liquid with a high Ca/Al ratio. In the following we argue that whereas the Arndt sequential melting model is unsatisfactory as an explanation for the very high CaO/Al_2O_3 ratios of the Barberton-type komatiites, it can be used in a modified form to model the lower CaO/Al_2O_3 ratios seen in the majority of PK.

The critical parts of the model as presented by Arndt (1977) are: (a) that under some circumstances garnet will melt before clinopyroxene, and (b) that this results in the enrichment of Al in the melt and its depletion in the residue. Arndt (1977) uses the experimental results of Mysen & Kushiro (1977) on a lherzolite nodule to demonstrate that in some cases garnet does melt before clinopyroxene. The nodule used is one of the least depleted samples occurring within kimberlites of South Africa. However, it has unusually low Al_2O_3, giving a CaO/Al_2O_3 ratio of 1.2 and an Al_2O_3/TiO_2 ratio of 11. (Both parameters are close to those observed in Barberton komatiites.) The data of Mysen & Kushiro (1977) on this sample indicate that even though garnet melts before clinopyroxene, about 25% melting is required to eliminate garnet. At this level of melting, a substantial amount of clinopyroxene would have melted and this would tend to buffer the CaO/Al_2O_3 ratio of the liquid. Furthermore, Al released into the melt by the melting of garnet would be partitioned between the liquid and the two pyroxenes. We suggest, therefore, that the net effect of Al partitioning and clinopyroxene melting would tend to buffer the CaO/Al_2O_3 ratio of the melt and the residue would therefore not have an anomalously high CaO/Al_2O_3 ratio.

We believe that Arndt (1977) is correct in his view that some melt did leave the source of the komatiites; the consistent light-REE-depleted patterns of the PK (Arth *et al.* 1977, Sun & Nesbitt 1978) provide the critical evidence in favor of it. As the ensuing discussion indicates, we also believe that this melt represented only a small percentage of melting or alternatively, if a large percentage melting was involved, there must have been a high percentage of melt retention. This argument is based on the observed Al/Ti, Ca/Ti ratios of komatiites which, apart from the ADPK, are consistently close to chondritic values.

The Al_2O_3/TiO_2, CaO/TiO_2 ratios of the residue (*i.e.*, PK source) are controlled by the original composition of the source, the composition of the initial melt (which in turn is controlled by the relative mineral stabilities at those P–T conditions) and the amount of melt retention. We can calculate these ratios if we assume a mantle composition, amount of melt retention and make some estimate of the relative degree of incompatibility of Ti, Al and Ca. The general conclusion is that irrespective of the composition chosen, if Ti is more incompatible than Al and Ca and if melt is lost then the Al/Ti and Ca/Ti ratios of the residue will increase. For example, if we assume a chondritic mantle model with 4.08% Al_2O_3, 3.36% CaO and 0.2% TiO_2 (Sun & Nesbitt 1977) and also assume that all of the Ti and only half of the Al and Ca enter the melt, then the resultant Al/Ti, Ca/Ti ratios in the source will be dependent on the amount of melt retained. With a 10% melt retention, the Al_2O_3/TiO_2 ratio of the residue would be over 100 whereas the CaO/TiO_2 ratio would be over 90. If 50% of the melt is retained, the ratios become 30 and 25, respectively. Alternatively, if 75% of the Al and Ca enter the initial melt, then 10% melt retention produces Al_2O_3/TiO_2, CaO/TiO_2 ratios of 66 and 55 whereas 50% retention produces ratios of 25 and 21.

In the case of the Barberton material, the sequential-melting model predicts that if the original source of the Barberton komatiites had chondritic Al/Ti, Ca/Ti ratios, then these komatiites should have ratios greater than this. In fact Barberton komatiites are characterized by abnormally low Al_2O_3/TiO_2 ratios but have near-chondritic CaO/TiO_2 ratios. Whether these features reflect the source character or an unusual melting history, we believe that other geochemical parameters (see below) indicate that garnet must be involved. However, before discussing this aspect of komatiite genesis we examine the possibility that sequential melting can explain the high CaO/Al_2O_3 ratio of AUPK, *i.e.*, those komatiites with ratios of about 1 as opposed to 1.5 for ADPK.

Sequential melting and high Ca/Al ratios

Figure 5 is a plot of CaO/TiO_2 *versus* Al_2O_3/TiO_2 ratios for several komatiite provinces and also for modern mid-ocean-ridge basalts (MORB). To facilitate comparison, the data are split into individual provinces and the chondritic values for CaO/TiO_2 (16.8) and Al_2O_3 (20.4) are plotted on each diagram. MORB data show a strong trend from low Ca/Ti, Al/Ti ratios toward chondritic values (*cf.*, Fig. 2) and the slope of the trend approximates a series of liquids whose CaO/Al_2O_3 ratios are close to chondritic (0.82). Comparison of this trend with that of Munro shows that although the Archean trend starts where MORB ends, it has a different slope. This slope is such that CaO/TiO_2 and Al_2O_3/TiO_2 ratios are about equal, resulting in a CaO/Al_2O_3 ratio close to 1. Other komatiite provinces (Fig. 5b–d) show this general tendency but have a more pronounced CaO increase relative to Al_2O_3, which results in Al_2O_3/TiO_2 remaining near-chondritic whereas CaO/TiO_2 is greater than chondritic.

There does not seem to be any logical reason why the Archean mantle should have had chondritic Al/Ti ratios but higher Ca/Ti ratios and then evolved such that present-day Ca/Ti ratios become chondritic. For this reason, we suggest that the higher Ca/Al ratios of Archean

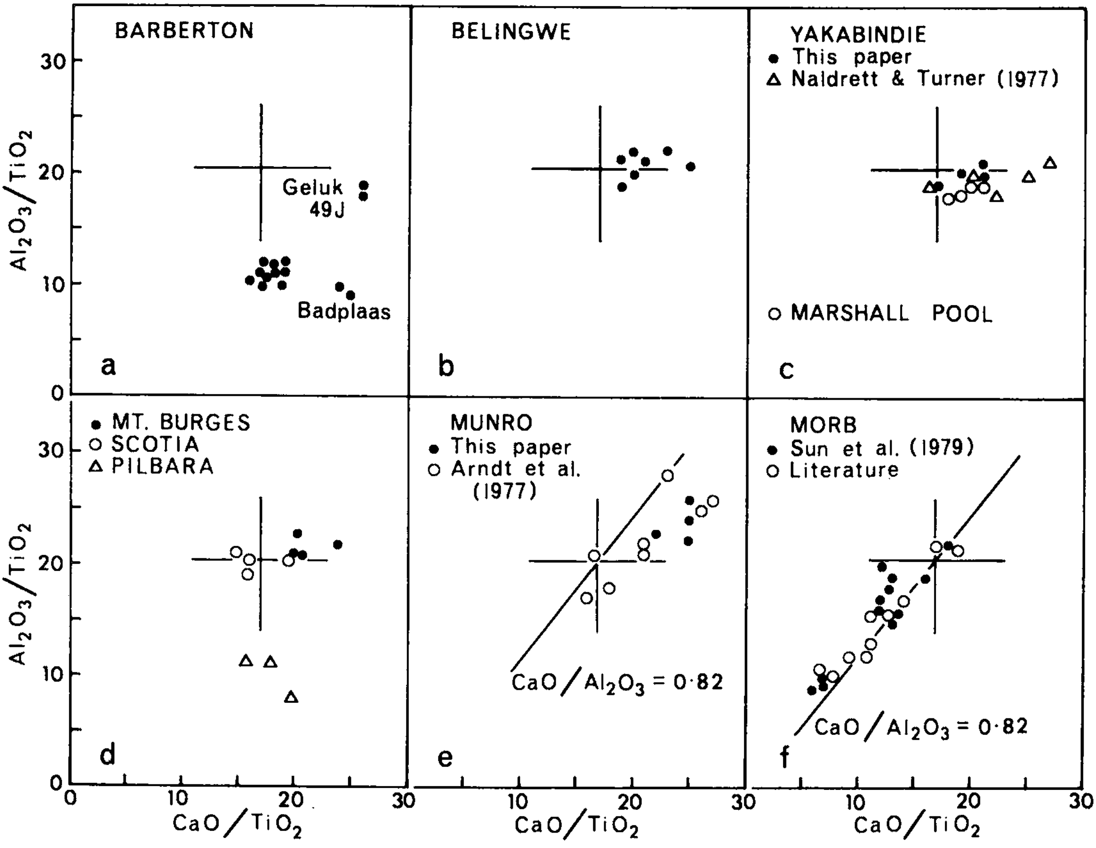

FIG. 5. CaO/TiO_2 *versus* Al_2O_3/TiO_2 plot for MORB and several komatiite provinces. The cross in the centre of each figure represents the intersection of chondritic values for these element pairs. Data for MORB chosen on the basis of high MgO/(MgO+FeO*).

komatiites are probably a result of repetitive or sequential melting processes rather than being due to intrinsic differences between the Archean and present-day mantle. This view is based on the observed depleted LREE patterns of peridotitic komatiites (*e.g.*, Sun & Nesbitt 1978a) which reach their maximum development in the Munro komatiites (Arth *et al.* 1977, Sun & Nesbitt 1978a) and which suggest effective previous melt extraction. We can model the observed CaO/Al_2O_3, Al_2O_3/TiO_2 and CaO/TiO_2 ratios of komatiites on the assumption that sequential melting is involved. As discussed in the previous section, if Ti is incompatible relative to Al and Ca and if melt retention is low (< 50%), then the end result of sequential melting is to produce very high Al/Ti, Ca/Ti ratios in the residue. Clearly then, in order to keep these ratios close to those observed, the percentage of melt retention must be high. Furthermore, if we assume that a CaO/Al_2O_3 ratio of about one is a result of sequential melting and is not an intrinsic value of the Archean mantle, the model must be modified to allow Ca to remain in the source relative to Al. For example, if 75% Al and 25% Ca available in the source mantle enter the first melt and 60% of this melt is retained, the resultant Al_2O_3/TiO_2, CaO/TiO_2 ratios of the source would be 24 and 25, respectively.

Using this model the first melt would have a CaO/Al_2O_3 ratio of 0.27 whereas that of the residue would be 1.06. However, melts with such low ratios are exceedingly rare (*e.g.*, some of the more fractionated leucite lamproites of Western Australia, described by Prider 1960); in fact, there is a tendency for initial melts to have high CaO/Al_2O_3 ratios (*e.g.*, in kimberlites this ratio generally exceeds 1.5). Thus if the sequential melting model requires a small-percentage-melting event, the resultant melt will in all probability have a CaO/Al_2O_3 ratio much greater than the 0.3 value modeled above. If the percentage melting involved in the event was large (with high retention) then the resultant melt would have a CaO/Al_2O_3 ratio close to that of the assumed source (*i.e.*, 0.8). We therefore conclude that the high CaO/Al_2O_3 (about 1) of AUPK cannot be modeled using an initial melt with a low Ca/Al ratio as one of the parameters.

In the previous discussion, we have assumed that in the sequential melting model, Ti is completely incompatible. This may not be the case, particularly if low degrees of melting are involved. To some extent this can be tested by referring Ti to Zr. Most AUPK (and also primitive Archean tholeiites) have Ti/Zr of 110, approximately the chondritic value (*e.g.*, Sun & Nesbitt 1977). This indicates that in the sequential melting model, the early melts also had this value (we assume that 110 is the mantle value) or were insufficient in volume to affect the residue. Data on kimberlites (*e.g.*, Ferguson *et al.* 1975, Emeleus & Andrews 1975) show that this ratio is about 50, indicating that in these melts the two elements are decoupled and that Zr is more incompatible than Ti (*cf.*, Sun *et al.* 1979).

If we assume that Ti was not completely incompatible during the generation of the early melts the necessity to have sufficient melting and also retain large amounts of this melt would be alleviated. For example, if 20% CaO and Al_2O_3 and only 50% of the available TiO_2 entered the melt and 30% of the melt were retained, the Al_2O_3/TiO_2 and CaO/TiO_2 ratios of the residue would be 27 and 22, respectively.

However, the assumption regarding Ti incompatibility does not account for the CaO/Al_2O_3 ratio of about 1 (in the above example it would be 0.8), and in the following, we present a sequential melting model designed to account for the CaO/Al_2O_3 ratios of AUPK (*i.e.*, ratios close to 1). The model is based on the assumption that the initial mantle source had chondritic ratios for Al/Ti and Ca/Ti and that the early melts which removed the light REE approximated kimberlite in composition (*i.e.*, had high Ca/Al ratios and Ti was not incompatible). Under these circumstances, the mantle residue after an initial melt extraction would have Ca/Al ratios slightly lower than chondritic. Further extensive melting would exhaust clinopyroxene and garnet from the source, thus liberating Ca and Al. However, if some orthopyroxene remains in the source, part of the Al would be held back from the melt, resulting in a high CaO/Al_2O_3 ratio in the liquid. Table 2 represents one attempt to model this process, largely controlled by using a CaO/Al_2O_3 ratio of 2 for the initial melt removed from the komatiite source (Col. III).

TABLE 2. CaO/TiO_2 AND Al_2O_3/TiO_2 RATIOS AND SEQUENTIAL MELTING

	I	II		III	IV	V
	Starting[A] Composition	Average Kimberlite[B] Type 1	Type 2	1st Melt[C]	1st Residue[D]	2nd Melt[E] (PK)
Al_2O_3	4.08%	4.4%	4.9%	.14%	3.94%	3.08%
CaO	3.36	7.6	10.6	.28	3.08	3.08
TiO_2	.20	2.3	2.0	.05	.15	.15
Al_2O_3/TiO_2	20.4	1.9	2.5	2.8	26	20.5
CaO/TiO_2	16.8	3.3	5.3	5.6	20.5	20.5
CaO/Al_2O_3	.82	1.7	2.2	2.0	.78	1.0

(A) Assumed starting composition is chondritic (Sun & Nesbitt 1977). (B) Dawson (1960). (C) First melt has ratios that approximate kimberlite; the values represent amount of oxides removed from the starting composition and not oxide contents of the melt itself. (D) Residue = Col. I - Col. III. (E) Second melt assumes some Al retention in the source; the values are amount of oxides removed from the residue, not oxide contents of the melt itself.

The choice represents one extreme and were it not for the small amounts of melt involved, would exacerbate the problem of obtaining a CaO/Al_2O_3 ratio close to one in the source. The important implication of the model is the retention of Al by orthopyroxene at the time the komatiite melt is generated.

If the model involving small amounts of melting is applicable it is clear that the melts did not reach the surface; it seems likely that they leaked upward to form zones of enriched mantle. If the model is not applicable we have to envisage larger amounts of melting and this would infer that Ti would be incompatible. The net result of this would be the necessity to retain a large percentage of this melt.

The model has implications as far as modern MORB is concerned. Evidently, melting of the modern upper mantle produces MORB liquids with chondritic CaO/Al_2O_3; when the extent of melting is large, the Al/Ti and Ca/Ti ratios also become chondritic (Fig. 5 and Sun & Nesbitt 1978b). Therefore, we infer that if orthopyroxene is in the residue of MORB then it does not hold back Al from the liquid. This indicates that at the point of separation of the liquid from its source, the pressure was low enough to prevent formation of aluminous pyroxene.

One further implication of sequential melting is that if MORB are the products of sequential melting, then the arguments raised concerning increasing CaO/TiO_2 and Al_2O_3/TiO_2 ratios should apply. In fact, few MORB have such high ratios. One possible explanation is that during the melting process which produces the LREE depletion in the MORB, Ti behaves compatibly and is largely retained by the source. This would have the effect of preventing an increase in the ratios in the MORB source. The reason why Ti behaves as a more incompatible element in the development of the komatiite source (as it must do in order to increase the CaO/TiO_2 ratio) could be related to factors such as higher temperature (and hence lower mineral-melt K_d), residual mineralogy or higher degrees of melting in the initial phase of source development.

Garnet as a mechanism for high Ca/Al ratios

In the preceding sections we have pointed out that the problem of high Ca/Al ratios in komatiites resolves itself into two separate explanations. Most komatiites (*i.e.*, AUPK) have CaO/Al_2O_3 ratios close to 1; we suggested above that a sequential melting model may be an explanation. However, komatiites from the type area have much larger ratios (about 1.5); in addition to their depleted heavy REE patterns (Sun & Nesbitt 1978a), this suggests that garnet is responsible. Green (1975) has suggested that garnet separated by disaggregation of the upwelling source and this effectively removed Al from the source material without re-equilibration taking place. Alternatively, but less probably, garnet may have crystallized and settled through an ascending column of komatiitic magma. Whatever the mechanism, Al depletion is remarkably constant because komatiites from Barberton (Table 1), Forrestania (Purvis 1978), Pilbara (Table 1) and Ravensthorpe (Baxter 1971) all have Al_2O_3/TiO_2 ratios close to 11. This implies that if garnet was responsible then a constant amount (presumably all) was lost. In the case of garnet crystallizing from the melt, then not only a constant amount of garnet must have crystallized but in order to achieve the high Ca/Al ratio the amount of clinopyroxene crystallized would have to be small. This places constraints on the P–T conditions of crystallization (e.g., O'Hara *et al.* 1975).

The influence of garnet on komatiite genesis can be tested using several geochemical parameters, particularly the heavy REE. Figure 6 shows the REE patterns for several Barberton samples (Sun & Nesbitt 1978a). With the exception of 49J, all show heavy REE depletion. As 49J does not show Al depletion (its Al_2O_3/TiO_2 ratio is close to chondritic) we would predict that garnet extraction was not involved and therefore its heavy REE pattern should be flat. Sample Comp. B, a composite sample (Purvis 1978) from Forrestania (W. Aust.), has many features in common with the Barberton komatiites, including low Al_2O_3/TiO_2, high CaO/TiO_2 and depleted heavy REE. For comparison, we have plotted a typical REE pattern of an AUPK from the eastern Yilgarn Block (sample 331/347). In this case, the heavy REE are flat [$(Yb/Gd)_N$ is close to 1 compared to about 0.7 for the Barberton samples] and the Al_2O_3/TiO_2 is chondritic (Sun & Nesbitt 1978a).

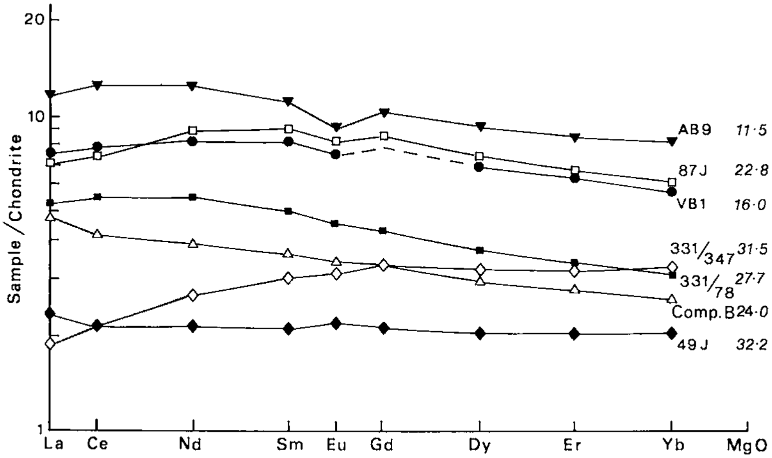

FIG. 6. Rare-earth-element patterns (after Sun & Nesbitt 1978a) for Barberton samples. The pattern for an STPK from Western Australia (331/347) illustrates a strong light REE depletion which is common for most STPK other than Barberton types. Composite B is from Forrestania, Western Australia and represents material similar to Barberton komatiites. The patterns also illustrate the heavy REE depletion of the Barberton samples.

Hence the REE data are consistent with a garnet-extraction model; we can predict that if the CaO/Al_2O_3 ratio is high and the Al_2O_3/TiO_2 ratio is low, there will be depletion in the HREE (Fig. 7).

In addition to heavy REE and Al, garnet will also remove elements such as Sc; to test this we have plotted the Sc–Zr data from Table 1 (Fig. 8). Whereas the majority of peridotitic komatiites (*i.e.*, AUPK types) plot close to the chondritic line (Sc/Zr=1.4), the Barberton (except 49J) and Pilbara material plot below the chondritic line, indicating either Zr enrichment or Sc depletion. This can be tested by referring Zr and Sc to Ti. Sample 49J has a Ti/Zr ratio of 120, close to the chondritic value of 110 (Sun & Nesbitt 1977). Other Barberton STPK have slightly lower values (average 93) indicating a relative enrichment of Zr over Ti. This is not unexpected in view of the slope of the heavy REE pattern and the relative position of Ti to Zr along this pattern (Sun *et al.* 1979). The chondritic Ti/Sc value is 78 (Sun & Nesbitt 1977), very close to the value for 49J whereas the remaining Barberton samples have ratios close to 100 (average 105). We take this as confirmation of strong Sc depletion in those STPK with heavy REE depletion. ADPK also show V depletion relative to Ti. Ti/V ratios for Barterton komatiites are close to 20, except 49J with a value of 13. AUPK have values of about 14. Hence the REE, Al, Sc and V data support the view that there is significant depletion of these elements in the source of ADPK; this is consistent with a garnet extraction model.

If this melting model is not used, the alternative is to assume that the abnormally high CaO/Al_2O_3, low Al_2O_3/TiO_2 ratios are a reflection of the nature of the source mantle. Cawthorn & Strong (1974) have suggested that the mantle has a layered structure with a relatively higher clinopyroxene/garnet ratio in its upper parts. Melting of this upper zone gives melts with high Ca/Al ratios. For reasons given elsewhere (Nesbitt & Sun 1976) we find the layered mantle model unsatisfactory, but if accepted it follows that most komatiites (AUPK) come from the lower parts of the layered structure. Our own preference (if mantle heterogeneity is the cause of the difference between AUPK and ADPK) is a model with lateral mantle heterogeneities involving variations in proportions of garnet.

Discriminant diagrams

The recognition of metamorphosed mafic igneous rocks as komatiite is largely based on geochemistry. We emphasized earlier that in most cases there is little doubt whether an ultramafic rock is a komatiite because in most cases spinifex-textured olivine or its alteration products are preserved. Hence the major problem is the geochemical discrimination of frac-

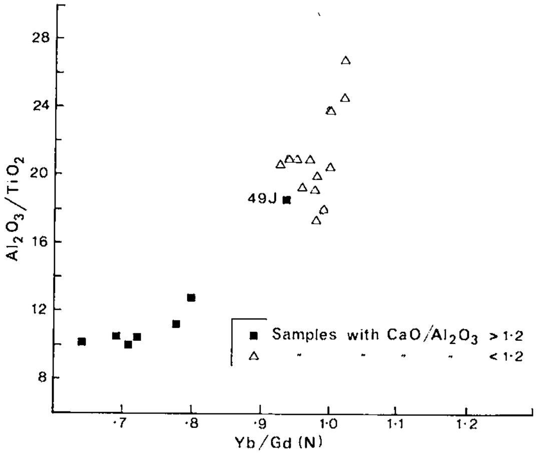

FIG. 7. Al_2O_3/TiO_2 *vs.* Yb/Gd (N) plot for some Archean STPK samples. The general pattern of Al_2O_3 depletion (relative to TiO_2) and heavy REE depletion is clear. The diagram draws attention to the correlation between high CaO/Al_2O_3 and heavy REE depletion.

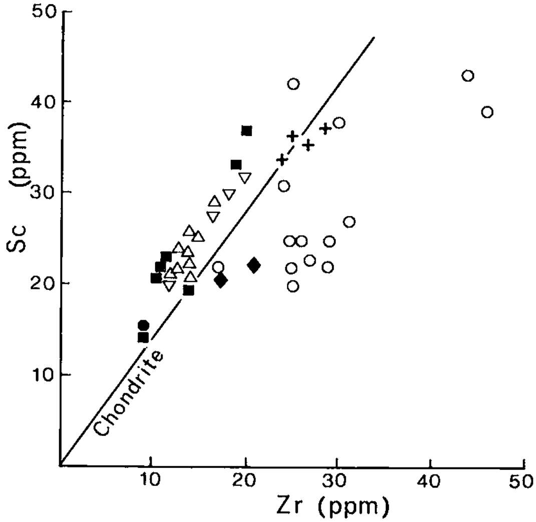

FIG. 8. Sc–Zr plot. The aberrant data point is sample AB9, a basaltic komatiite; its position is presumably due to fractionation. The general depletion of Sc relative to Zr for the Barberton samples is brought out in this plot. Symbols as for Figure 1.

tionated basaltic komatiites from primitive tholeiites.

Two possible rock associations seem to be developed. In the first, *e.g.*, at Barberton (Viljoen & Viljoen 1969a; Table 1, this paper) and Forrestania (Purvis 1978) the basaltic komatiites, in contrast to the associated tholeiites, are characterized by low Al_2O_3/TiO_2. The distinction in this case is relatively easy and also manifests itself in high CaO/Al_2O_3 ratios. In the second association, *e.g.*, Munro (Arndt *et al.* 1977) the basaltic komatiites have near-chondritic Al_2O_3/TiO_2 ratios making the distinction problematic. Thus Arndt *et al.* (1977) point out that for the Munro area, the CaO/Al_2O_3 ratio is of little use in distinguishing between what they recognize as komatiite and tholeiitic rocks. Instead, they have suggested that parameters such as Al_2O_3 *vs.* $FeO^*/(FeO^*+MgO)$ and SiO_2 *vs.* TiO_2 are perhaps the most useful criteria.

Figure 9 is a plot of $FeO^*/(FeO^*+MgO$ *vs.* Al_2O_3 for Archean rocks and various basaltic types including mid-ocean ridge basalts (MORB). In Figure 9B, Munro komatiites plot to the left and Fe-rich tholeiites plot to the right of the line. Although Arndt *et al.* (1977) specifically state that the diagram is of use only in areas where both tholeiitic basalts and peridotitic komatiites occur, there is an increasing tendency to adopt and use it as a universal discriminant (*e.g.*, Schwarz & Fujiwara 1977). Naldrett & Goodwin (1977) have suggested a modification to the diagram such that basalts plotting within the triangular area in the high Al_2O_3–low $FeO^*/(FeO^*+MgO)$ part of the diagram (area ABC, Fig. 9A) be designated intermediate basalts. Basalts of this type, with less than 1% TiO_2, are believed to be komatiitic in nature, particularly if the MgO content exceeds 8.5%, whereas those with over 1% TiO_2 are believed to be transitional to the Fe-rich tholeiites.

In view of the prominence given to this dis-

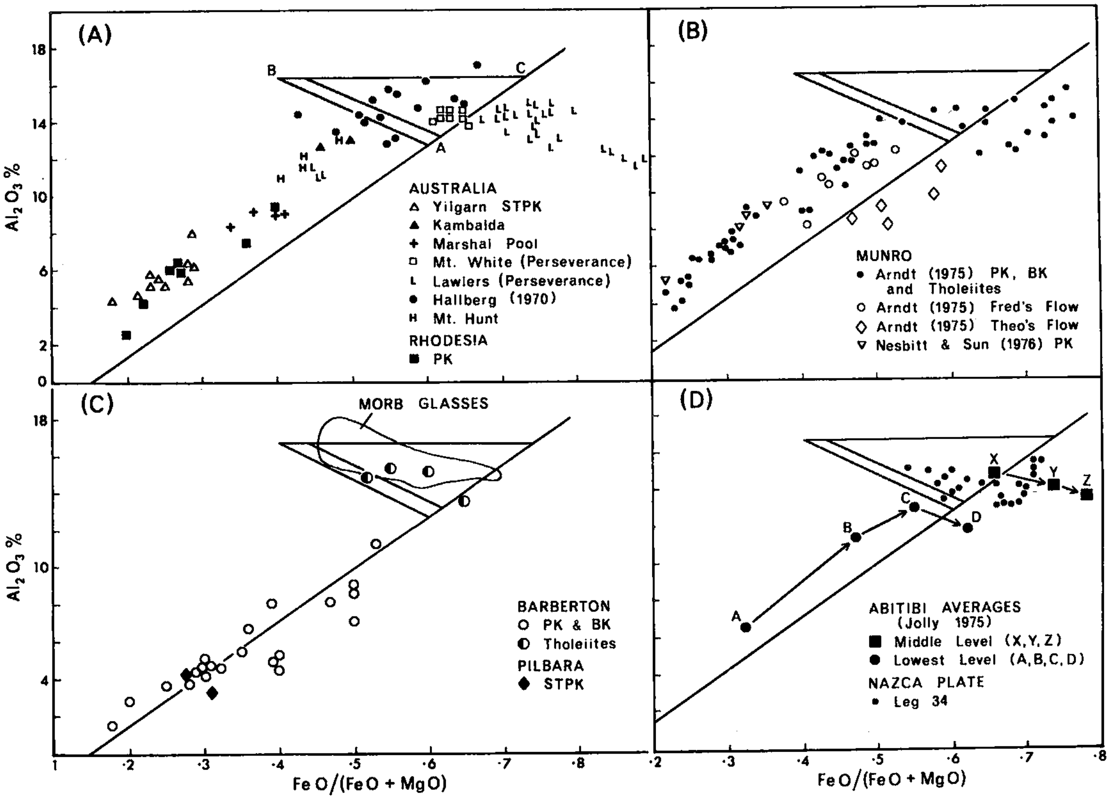

FIG. 9. Al_2O_3 *versus* $FeO^*/(FeO^*+MgO)$ plots where FeO^* equals total iron. (A) Data from Hallberg (1970) are a selection of representative samples; some data from Lawlers are from Naldrett & Turner (1977). Subdivision of the diagram is after Naldrett & Goodwin (1977). (C) Data for MORB glasses from Melson *et al.* (1977); other data, this paper. (D) Nazca-plate data from Mazzullo & Bence (1976).

criminant diagram it is profitable to discuss it further in terms of both Archean and younger mafic rocks. For our purposes the diagram can be divided into three areas: the low Al_2O_3–low *fe* (=FeO*/FeO*+MgO) portion (lower left), the zone of intermediate basalts (ABC) and the high Al_2O_3–high *fe* portion (upper right). The field of ultramagnesian liquids and olivine cumulates forms a relatively smooth pattern of increasing Al_2O_3 and *fe* which is essentially an olivine control line. The ADPK from Barberton form another group, subparallel to the main komatiite trend; this trend crosses from the komatiite into the tholeiite part of the diagram (Note that Arndt *et al.* (1977) recognized this feature and suggested that the Barberton rocks could be identified as komatiites by their high CaO/Al_2O_3). The only samples (other than ADPK) that plot to the right of the line in this lower portion of the diagram are those from Theo's flow (Fig. 9B), a layered flow from Munro (Arndt 1975). Hence apart from this Munro material (which we discuss in the following) this portion of the diagram serves only to distinguish ADPK and AUPK, which is more easily done on the basis of Al_2O_3/TiO_2 ratios.

The upper portion of the diagram (Fig. 9) deals with high-Al_2O_3 rocks with variable *fe* values. Mid-ocean ridge basalt (MORB) glasses (Melson *et al.* 1977) plot in the intermediate zone; according to the Naldrett & Goodwin classification (1977) some would be classified as komatiitic because of their low TiO_2 and high MgO. More fractionated abyssal basalts, however, plot in the high-Fe tholeiite field (Fig. 9D) indicating a transition from high MgO-low Fe types (represented by the glasses) to more evolved types. The downturn in Al_2O_3 and increasing Fe/Mg ratio both indicate that plagioclase, olivine and pyroxene are involved in this fractionation.

Archean basalts that plot to the right of the discriminant line are those with high iron and low MgO (about 5%). These include the Munro tholeiites (Fig. 9B) and the Lawlers high-Fe tholeiites (Naldrett & Turner 1977, Sun & Nesbitt 1978a, Nesbitt & Sun, unpubl. data). It is clear that these samples cannot represent primary liquids as the *fe* values are too high (Green 1970). It follows that these basalts have parental liquid with lower *fe* values; we suggest that such liquids would plot to the left of the discriminant line (probably in the MORB field). This possibility is supported by the trend of the Lawlers data (Fig. 9A) and the averaged values given by Jolly (1975) for the basalts of the middle stratigraphic level of the Abitibi region (Fig. 9D).

The thrust of the preceding discussion is the implication that the subdivision into komatiite and tholeiite in the basaltic part of the Al_2O_3-*fe* diagram can equally be interpreted as the difference between near-primary tholeiitic and differentiated tholeiitic liquids. An alternative view is that the parental liquid of the Munro high-Fe tholeiites is itself high in iron and can be represented by the flow-top rocks of Theo's flow. The position of these rocks, shown in Figure 9B, make it tempting to argue that these do represent parental liquids. However, these "liquids" are of unusual type in that they have very low Al_2O_3/TiO_2 ratios (about 8–10), high MgO (about 9 to 14%), high FeO (12 to 15%) and highly variable CaO/Al_2O_3 ratios (0.75 to 1.04). Thus for some parameters these tholeiitic liquids have characteristics of Barberton komatiites (*cf.*, their relative position on the Al_2O_3-*fe* plot) whereas their higher FeO and TiO_2 contents contradict this interpretation. In view of this anomaly (which may cast doubt on the status of these samples as liquids) we suggest that they are not parental to the high-Fe tholeiites. To some extent, this is supported by Naldrett & Goodwin (1977) who suggest that intermediate basalt (*i.e.*, those plotting in the ABC triangle of Fig. 9A) with over 1% TiO_2, be regarded as transitional to the high-Fe tholeiites.

SiO_2–TiO_2 and MgO–TiO_2 diagrams have also been used by Arndt *et al.* (1977) to separate the tholeiite from the komatiite spectrum. Although SiO_2 contents are subject to alteration, the use of SiO_2 instead of Al_2O_3 avoids comparing low-TiO_2 andesites with high-TiO_2 basalts. The principal use of the diagrams is at the basaltic end of the mafic spectrum; at Munro there is a clear break at the 7% MgO level between basalts containing 0.8% and 1.2% TiO_2 (Arndt 1975). The question arises as to whether this is an intrinsic difference brought about by factors such as different source and fractionation history or whether the low-TiO_2 basalts (=komatiite) represent parental liquids which by crystal fractionation produce high-TiO_2 basalts (high Fe tholeiites). Without trace-element data on these basalts and their proposed parents no definitive conclusions can be reached.

In other Archean areas, *e.g.*, the Yilgarn Block, clear separation of basalts into discrete TiO_2 groups is not possible (Hallberg 1970). The pattern is further complicated by the observation that the TiO_2 of MOR basalt ranges from 0.6% upward and crosses the proposed komatiite–tholeiite boundary.

In other Archean areas, *e.g.*, the Yilgarn discriminant diagrams must be based on parameters that can be interpreted in terms of genetic processes. If there is a real difference between Archean basaltic komatiites and Archean tholeiites, then the difference must be related to such factors as different source characteristics or different degrees of melting. The presently available discriminant diagrams present an *ad hoc* approach to the problem; whereas they provide a simple working classification of Munro basalts (essentially based on high Fe and Ti), their wider application must await a demonstration of the causes of the differences in the basalt spectrum.

POST-ARCHEAN KOMATIITES

There are now several references to post-Archean komatiites; notable among these is a group of low-TiO_2 basalts that occur within ophiolitic sequences (Sun & Nesbitt 1978b). Gale (1973) described such rock types from a Paleozoic sequence in the Rambler area of Newfoundland; on the basis of their high Ca/Al ratios he suggested they were basaltic komatiites. Similar rock types have been described from Cyprus; Simonian & Gass (1978) believe they are komatiites. In this case not even the high Ca/Al definition is appropriate as recognition is based on low TiO_2 (about 0.2%) and high Cr and Ni concentrations.

The position of these basalts relative to Archean komatiites is ilustrated in Figure 2, which emphasizes their unusually low TiO_2 contents. We known of no komatiites from the type area or from other well-documented Archean terrains with such a characteristic. In our view, the use of the term *komatiite* for ence between them and typical MORB. Sun & these basalts is an attempt to express the differ- Nesbitt (1978b) have pointed to the unusual features of this low-TiO_2 rock type and have suggested that a specific environment (*e.g.*, wet melting of severely depleted mantle above a Benioff zone) may be responsible.

A further discriminant between komatiites and ophiolitic low-Ti basalts may be the TiO_2/P_2O_5 ratio, which in the former is close to 10 The available published P_2O_5 data on the low-Ti ophiolitic basalts are inconsistent, but we suggest the ratio may prove to be a valuable petrogenetic indicator. For example, the basaltic rocks from the Solomon Islands (Stanton & Bell 1969) claimed by Nisbet *et al.* (1977) to be komatiitic, have TiO_2/P_2O_5 ratios much lower (about 3) than the type komatiites. Furthermore the high MgO content of the rocks is directly attributable to cumulate olivine and the high Ca/Al to cumulate clinopyroxene (Stanton, pers. comm. 1977). Consequently their unusual chemical characteristics are to some extent artificial. However, their low Ti content is significant and perhaps a link to the low-TiO_2 ophiolitic basalts.

One further post-Archean komatiite occurrence merits discussion. Schwarz & Fujiwara (1977) have described "komatiitic" high-MgO lavas from the Proterozoic Cape Smith belt in northern Québec. We have examined these rock types and carried out further analytical work. The chemical characteristics of these lavas ($Ti/Zr = 100$, $TiO_2/P_2O_5 = 10$, $Ti/Y = 290$) all suggest that a large degree of melting is involved, as confirmed by textural relationships. We estimate that the crystal-free liquids contained up to 18% MgO and about 0.65% TiO_2. This would represent about 30% mantle melting if we take a pyrolite composition for the mantle. Furthermore the CaO/Al_2O_3 ratio of these rocks is close to or slightly greater than 1 (unlike the majority of the low-Ti ophiolitic basalts), again supporting their classification as komatiites. It is also of interest to note that these rock types are associated with nickel sulfide occurrences (Wilson *et al.* 1969) which in many respects are similar to those in the Yilgarn Block of Western Australia.

KOMATIITE GENESIS

There appears to be reasonable agreement that peridotitic komatiites with about 20–30% MgO represent primary liquids; it therefore follows that high temperatures must be involved. However, the view that they represent large-percentage mantle melts is by no means universally accepted. For example, Naldrett & Turner (1977) and Arndt (1977) argued that the viscosity of melts representing 20–50% melting would be so low as to preclude the retention of crystalline phases within it. Hence melts representing 60–80% of mantle melting (which in their view would be the level of melting necessary to produce peridotitic komatiites) could never be produced by a one-stage event. Therefore they suggested that melting would continue until a critical level was reached after which separation of the melt could not be prevented.

There are several issues associated with this model that are difficult to evaluate. Our general view is that although the viscosity arguments put forward by Arndt (1977) seem reasonable, there are other factors (*e.g.*, excessive turbulence) which may counteract them. For example, it is clear that for the model to have any credence, immiscible sulfide liquids, because of their density, would never reach the surface. Archean nickel sulfide deposits such as Scotia (Stolz 1979) and Kambalda (Ross & Hopkins 1975) provide strong evidence that olivine–liquid mixtures were able to accomplish this.

An important aspect of the sequential melting and separation models is the composition of the first liquid. Naldrett & Turner (1977) argued that this would be an Fe-rich basaltic melt produced by 25–30% melting. This is an unlikely composition, as such a liquid would have to be in equilibrium with its source mantle and also be capable (at the appropriate pressure) of crystallizing mineral phases left in the residue (Green 1970). The high *fe* value of the Fe-rich basalts precludes this possibility. In Arndt's (1977) model, the first-formed liquid has the composition of an olivine tholeiite and this represents 20% melting of the source. He proposed that the residue would be depleted in incompatible elements as well as clinopyroxene and garnet. A second melting event produces mafic komatiite lavas and a further melting gives the ultrabasic magmas. In this way, the PK liquids represent a small amount of melting of a residual source; as Arndt (1977) points out, they cannot therefore be regarded as representative of mantle composition.

Bickle *et al.* (1976) and Sun & Nesbitt (1977) have calculated Archean mantle compositions using PK liquids; these are in reasonable agreement with the estimates of Ringwood (1975) who used an entirely independent method. There is thus a contradiction between the predictions of the sequential melting model and the calculations based on komatiitic liquids. For example, Sun & Nesbitt (1977) estimated that the Archean mantle contained about 0.2% TiO_2 whereas the Arndt (1977) model would suggest that this value is a gross underestimation.

Bickle *et al.* (1977), using a model proposed by Cox (1978), argued that a more reasonable model is one of polybaric assimilation in which a magnesian liquid separates from a dunitic or harzburgitic residue and on moving upward assimilates a crystalline fraction. They suggest that this fraction could be garnet lherzolite because they believe an aluminous phase to be necessary to control the compositions of the PK. This model thus effectively circumvents the viscosity arguments raised by Arndt (1977) because the liquid never loses contact with "fertile" crystalline phases. Whether such a process is possible depends on the balance of melting (due to adiabatic decompression) and crystallization produced by heat loss to the surroundings. An important implication of the model is that whereas the PK liquids give only a close approximation of mantle composition, they would give an accurate estimate of most elemental ratios.

The high temperatures necessary to produce peridotitic komatiites appear to be unquestionable. If the sequential melting argument is accepted, melting of the residue (to produce the ultramagnesian komatiites) would still require very high temperatures. Nesbitt & Sun (1976) argued that starting temperatures close to 1900°C are required; to achieve this means bringing material from as deep as perhaps 400 km. The most acceptable model is one in which diapiric plumes or "blobs" become thermally unstable and move upward. In some cases (*e.g.*, Bickle *et al.* 1975), sialic crustal rifting results and this may be the general case rather than the exception. For example, the high-Mg lavas of the Cape Smith–Wakeham belt (northern Québec), which we believe to be komatiites (see also Schwarz & Fujiwara 1977), erupted onto sialic crust. In other areas, *e.g.*, Scotia (Nesbitt & Sun 1976, Stolz 1971), the peridotitic komatiites erupted onto silicic volcanic rocks indicating a complex crustal history at these sites. In many cases, komatiite volcanism is preceded by tholeiitic lavas (*e.g.*, Scotia and Kambalda) and may in some cases be overlain by tholeiitic basalts. This suggests that both komatiites and tholeiites may be genetically linked; we suggest that the principal difference is in the degree of melting. In this sense, komatiites are simply an extension of tholeiites and we consider that the difference between AUPK and ADPK may be a more fundamental difference than that between komatiites and tholeiites (Purvis 1978).

CONCLUSIONS

(1) Peridotitic komatiites can be recognized and defined by the presence of spinifex textures. Their general geochemical parameters, particularly the chondritic ratios of many element pairs (Nesbitt & Sun 1976, Sun & Nesbitt 1978a), suggest that large amounts of mantle melting are involved. There is as yet no suitable definition of basaltic komatiites except that they are high-Mg basaltic liquids.

(2) The high CaO/Al_2O_3 ratio of Barberton komatiites (1.5) is due to aluminum depletion whereas the majority of other komatiites have CaO/Al_2O_3 ratios close to 1. We refer to these two types as aluminum-depleted komatiites (ADK) and aluminium-undepleted komatiites (AUK), respectively. This terminology refers to both peridotitic and basaltic types, *i.e.*, ADPK, ADBK (depleted) and AUPK, AUBK (undepleted).

(3) ADK are characterized by low Al_2O_3/TiO_2 ratios (about 11) and by heavy REE, Sc and V depletion; these are not adequately explained by sequential melting models. We suggest that garnet loss from the source is a possible means of explaining ADK geochemistry. Alternatively, the differences between komatiite types reflect significant lateral mantle heterogeneity.

(4) The CaO/Al_2O_3 ratios of AUK can be explained by sequential melting provided aluminous orthopyroxene remains in the source.

(5) A spectrum of partial melting in the Archean resulted in a series of liquids ranging in composition from tholeiitic to komatiitic. Geochemical relationships, particularly the REE, suggest that the basaltic komatiites are not the products of fractional crystallization of peridotitic komatiites.

(6) Post-Archean komatiites are rare; in our view, low-Ti basalts found in some Phanerozoic ophiolites do not conform to the definition of komatiite.

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